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6 DIGITAL CARTOGRAPHIC STUDY AND BENCHMARK

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The key problem in the automatic generation of digital terrain data is the matching of conjugate points on a stereo pair of aerial photographs in an accurate and timely manner. The work described in this report centers around the development of suitable algorithms and systems procedures to perform this matching task in an all-digital environment.

Two approaches to automatic image matching have been investigated; a strip

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processing approach and a block processing approach. Of the two approaches, it has been found that the block processing approach is more adaptable to the requirements of digital terrain data collection. Therefore, this approach is being investigated further for implementation in an array of fast, microprogrammable processors to provide a benchmark of matching system parameters and performance.

ABSTRACT

The key problem in the automatic generation of digital terrain data is the matching of conjugate points on a stereo pair of aerial photographs in an accurate and timely manner. ~~The work described in~~ this report ~~centers around~~ describes the development of suitable algorithms and systems procedures to perform this matching task in an all-digital environment.

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1.0 INTRODUCTION

Automatic systems for the compilation of digital terrain data must be fast, accurate and flexible. In addition, the cost of such systems must be in proportion to the quality of data they generate. The need for automatic cartographic systems is unquestioned, considering the volume of photographic data in need of processing. What is important to consider is the optimum technology required to perform this task of cartographic data processing.

This technical report is a summary of the first phase of ongoing work in the development of fast, accurate and flexible algorithms and systems to produce the desired mapping products.

The primary area of consideration in generating digital terrain data is the automatic matching of conjugate points in a stereo pair of aerial photographs. This is the area in which computational speed is of utmost importance and in which a great deal of algorithm sophistication is required. Clearly, all of the research is not yet in regarding the optimum approach for such a task.

Therefore, two approaches to the problem of image matching which have been used in the past by Control Data for automatic registration and change detection purposes are being investigated. The study described in this report involves the redesign and modification of the two approaches to efficiently and accurately process stereo imagery. The overall goal of the effort is to choose the better approach for implementation in fast, microprogrammable processors as a demonstration and verification of feasibility.

The two image matching approaches, called the strip approach and block approach, have been generally described in a previous technical report [1], and these aspects will not be re-discussed here. Only the modifications, new aspects, and new results will be treated. Suffice it to say that since both approaches utilize the correlation coefficient as the image matching metric, what the study is really comparing are the two philosophies behind the matching approaches.

The strip processing approach is very fast and production oriented. It is fast because it incorporates a line-by-line error correcting process. That is, the process knows where on the image to move next based on the errors it sees now. On the other hand, the block approach is a slower process, incorporating a a rather deterministic predict-ahead mechanism. The study has shown that because of these differences in approach, differences in the output digital terrain data occur and a number of trade-offs emerge.

2.0 MODIFICATION OF STRIP APPROACH: INTRODUCTION

Throughout this section of the report, we will be addressing the problem of successfully matching stereo imagery with an automatic strip process. This automatic strip processor will be referred to as program TRAK. We will discuss enhancements to TRAK made possible by the nature of stereo imagery. In addition, we will also address problems identified by an earlier attempt to use the strip process for this application. We will discuss solutions implemented for those problems and will indicate results both visual and statistical which we were able to achieve.

2.1 INCORPORATION OF EPIPOLAR Y-AXIS CONTROL

Previous applications of the strip process, in particular, side looking radar, ERTS multispectral data, and high resolution aerial photography, have included a correlation process using 5 patch sites separated by a distance of from 1 to 7 cells as indicated in Figure 2-1.

The effective size of the 5 sites is some patch height (user defined) by some patch width. A weighted accumulation of the required vector dot products provides an effective patch width dimension thereby reducing required memory for the actual inner products necessary to compute correlation. Using these 5 correlations, an interpolated maximum point on the correlation surface is found as illustrated in Figure 2-2. Deviations, or spatial error terms, are computed and then incorporated into warp equations as shown in Figure 2-3. Subsequently, these error terms drive the correction process.

For the application of matching stereo imagery, north and south sites were eliminated from the correlation and subsequent warp update process. Epipolar line geometry was incorporated into the process thereby providing y-axis control. X-axis matching is as performed in previous applications.

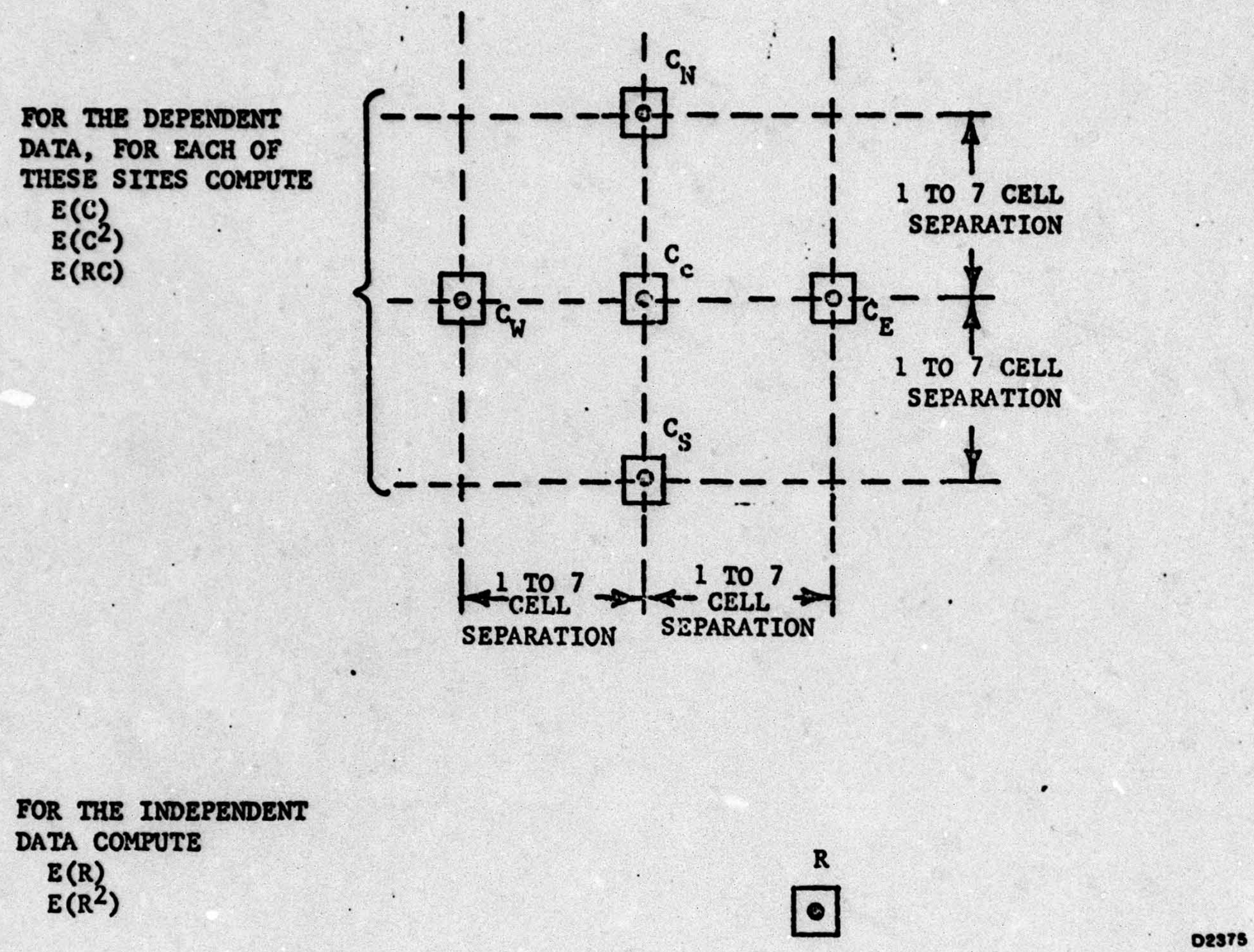

FIGURE 2-1. INNER PRODUCTS REQUIREMENTS PER STRIP

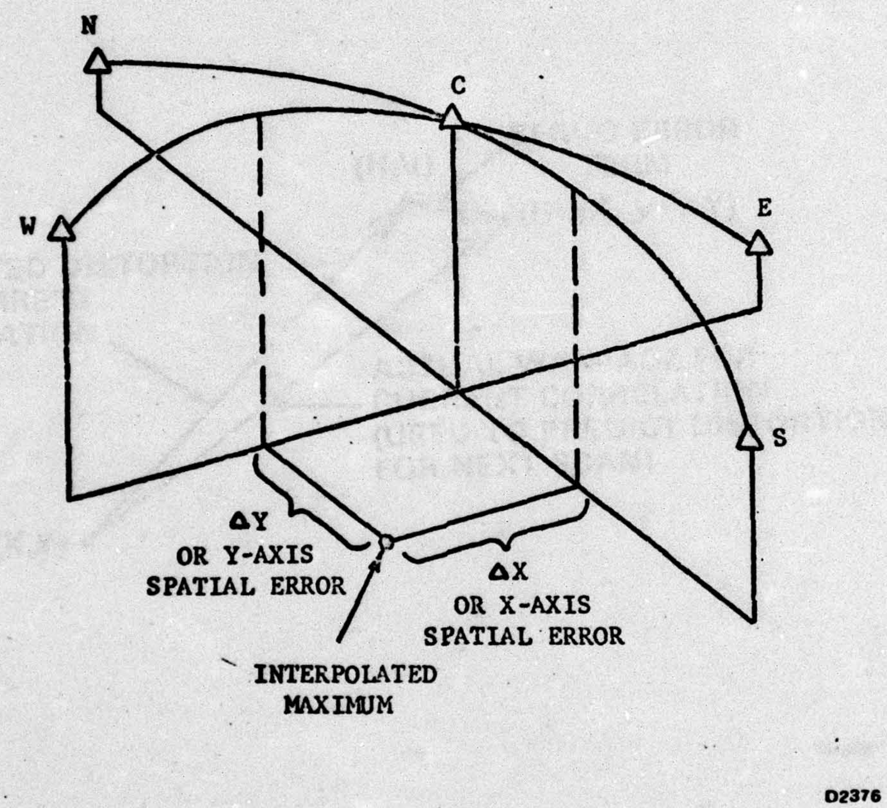

FIGURE 2-2. LOCATING MAXIMUM POINT ON CORRELATION SURFACE

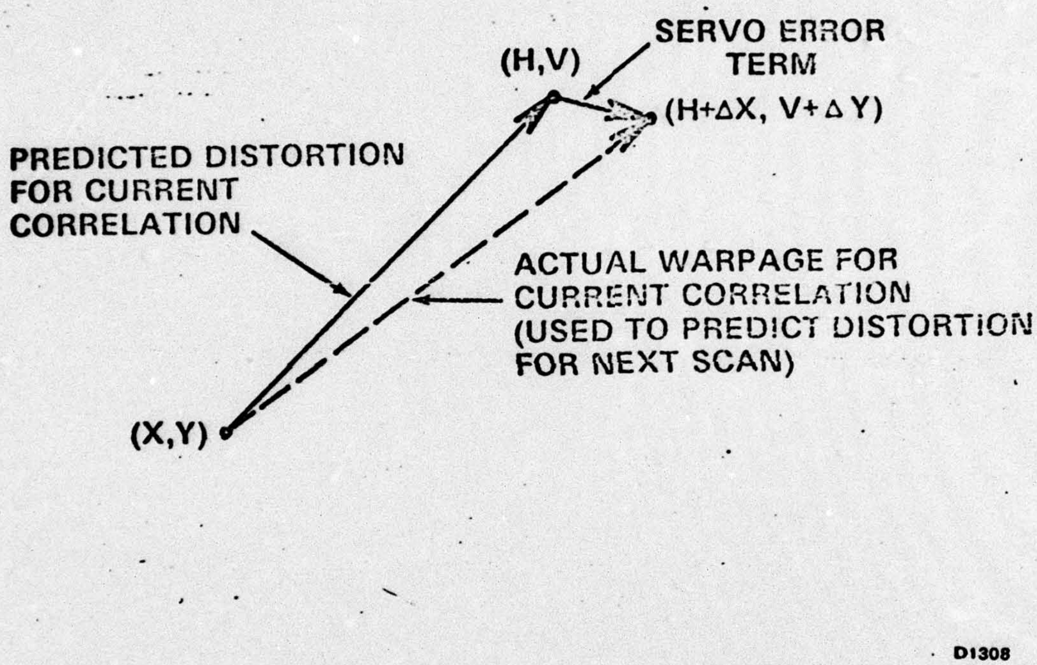

Figure 2-3. Relationship of the Maximum Correlation Coefficient Location as Used to Update Prediction Equation.

2.2 PROBLEMS IDENTIFIED BY PREVIOUS EXPERIENCE

Based on a previous study done by Digital Image Systems Division for USAETL, the following problems were identified in the strip process: First, the problem of effectively modeling the terrain in the creation of a synthetic scan line for subsequent correlation and match update; second, the problem of allowing the warp update process enough freedom to follow terrain, and yet retain enough stability in areas of dissimilarity; and third, the problem of interlocking strip information to effectively guide strips in hard to match areas. In the following 3 sections, we shall address each of these problems and the solutions we implemented for each.

2.2.1 APPROXIMATING HIGH ORDER EQUATION IN OBTAINING SYNTHETIC SCAN LINE

It is well known that the successful matching of stereo images requires the removal of x-parallax or differences in the placement of matching pixels in stereo images due to terrain relief. Since the TRAK program is a line-by-line process, it requires the creation of a synthetic scan line from the dependent image of the stereo pair for each line of the independent image. The proper creation of this synthetic scan line is of utmost importance in determining the current parallax signal, which in turn is used to drive the process. The building of this equivalent synthetic line is accomplished by defining positions within a buffer containing a section of the dependent image which are the equivalent of the strip centers in the independent image. This relationship is shown in Figure 2-4. Interpolation between strip centers is linear and uses a nearest neighbor criterion for the actual access of matching pixels. By retaining the linear interpolation technique and moving strip centers closer together, a much better approximation to the matching synthetic scan line, which is really a function of the terrain being imaged, can be obtained. This effectively gives TRAK the capacity to closely approximate a warp equation of an order which is entirely dependent on the terrain being encountered. In addition, correlation patch shaping is effected each line since inner product memories can be updated with information resulting

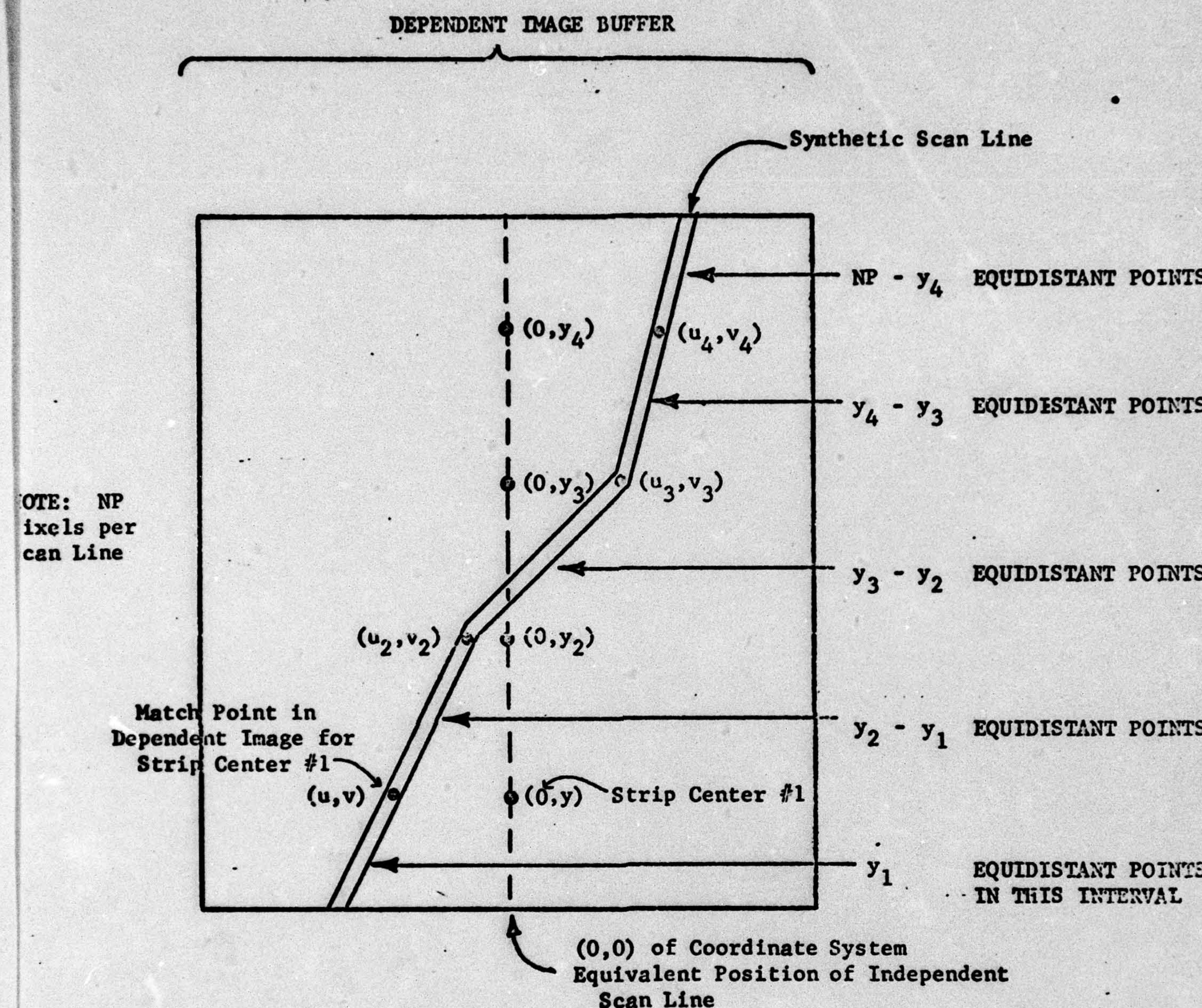

Figure 2-4. ACCESSING OF SYNTHETIC SCAN LINE FROM DEPENDENT IMAGE BUFFER WINDOW

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from the previous line's parallax signal.

2.2.2 CONSTRAINT VERSUS FLEXIBILITY IN THE CHOICE OF SYSTEM DAMPING

System damping in the TRAK program may be defined as the amount of filtering or smoothing needed to sufficiently remove noise effects in the error signal values produced by the correlation process. There are two unique and yet related methods by which the present version of TRAK is damped; the first is the rate at which inner products used for the correlation process are allowed to accumulate (definition of effective patch width), and the second is the rate at which error signals, resulting from location of the interpolated maximum on the correlation surface, are allowed to influence the predicted warp positions. In previous applications, for which the strip process has been used, studies showed a patch width of 10 lines, providing a correlation coefficient based on a combination of data smoothed over approximately 7.5 lines and providing independent spatial error signals approximately every 20 lines, was sufficient for most applications. It was only necessary to control the rate at which these error signals were allowed to update matching positions in the dependent image to achieve satisfactory results. For this application, however, it was discovered the frequency of independence in the error signals was required at a rate more often than 20 lines. In addition, it was found a much larger percentage of the error signal had to be incorporated during the warp update computations to maintain proper registration in areas of rapidly changing terrain. In obtaining the results indicated later in this report, an effective patch size of length 20 pixels and width defined by a smoothing factor with half-decay time of 5 lines, coupled with an error signal smoothing factor of 6 lines were used. This combination appears to have provided needed flexibility in adjusting position changes due to terrain encountered.

2.2.3 METHOD OF INTERLOCKING STRIP INFORMATION TO GUIDE STRIPS IN HARD TO MATCH AREAS

Throughout this discussion, we will refer to the task of guiding strips in hard to match areas as harnessing. In previous applications of the strip process, the technique used in satisfying this requirements is as illustrated in Figure 2.5. As the figure suggests, current strip positions are weighted by some measure of their accuracy and a first to fourth order equation (user defined) is derived using a least squares technique. Current strip positions are compared with least squares estimates and any strips exceeding some circular tolerance limit are corrected by averaging the current position and least squares estimate. Since the harness equation can be first to fourth order in complexity, this technique has proven acceptable in modeling all types of distortion encountered to date in applications for which the strip process has been used.

In the case of stereo images, this technique proved unacceptable. The problem becomes one of successfully approximating a frontal curve defined by current strip positions. The order of the equation necessary for this task is a function of the terrain which is currently being matched. It becomes apparent as the length of the scan line being matched increases, and the terrain within that scan lines varies, the complexity of the equation necessary to model that scan line becomes increasingly great.

Essentially what we implemented in order to overcome this problem was a number of piecewise linear approximations to the current frontal curve as illustrated in Figure 2.6. It was found that the information from 6 strips provided the needed stability for the least squares estimate to control strips within any particular segment of the frontal curve within some circular tolerance, typically 3 to 5 pixels. It was our conclusion that this would rarely be the case. In addition, the piecewise linear approximation has the added advantage of allowing much greater scan line lengths to be processed without the frontal curve modeling problem inherent in the greater length.

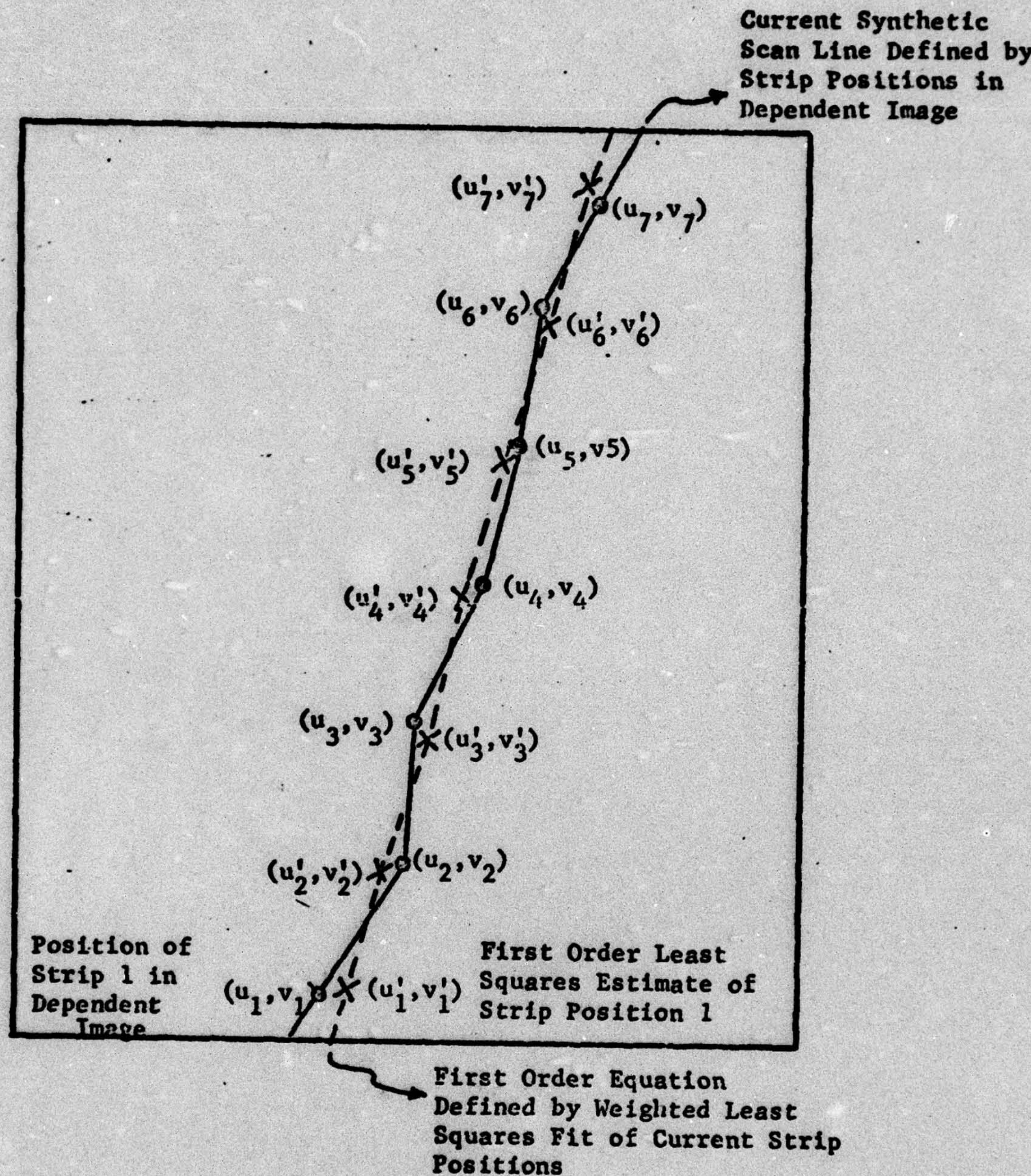

Figure 2-5. HARNESS TECHNIQUE FOR SIDE LOOKING RADAR

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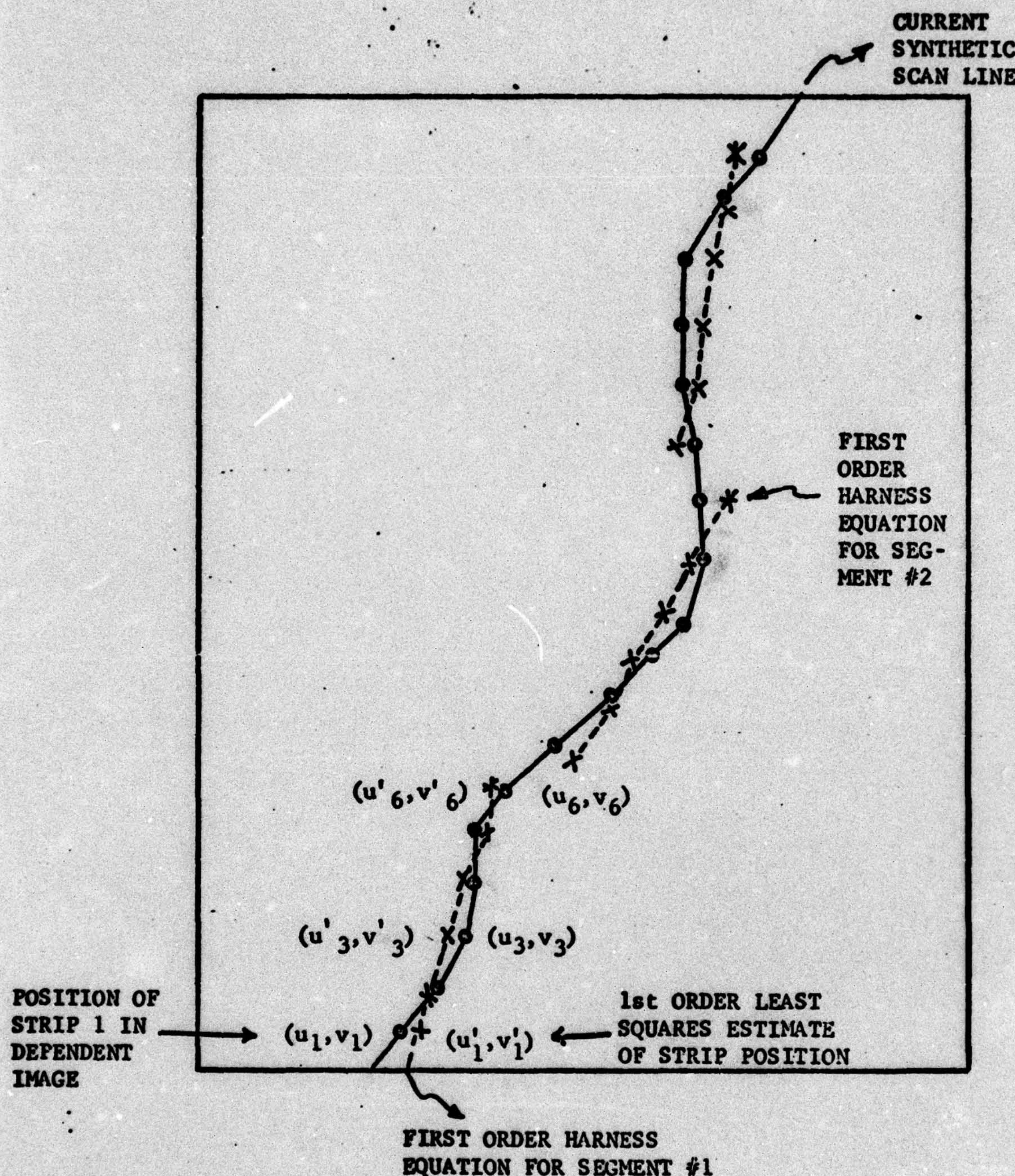

FIGURE 2-6. HARNESS TECHNIQUE USED FOR MATCHING STEREO IMAGES.

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3.0 MODIFICATION OF BLOCK APPROACH

Under a previous contract, a block processing software system was designed and delivered to USAETL for use with the DIMES System [1]. This block system was research-oriented and capable of being modified in a variety of ways for different applications.

For the present image matching effort, considerable changes have been made to this system, but the underlying philosophy of block processing or area correlation has remained constant. Under this concept a correlation area of certain dimensions is defined on one image of the stereo pair and a correlation search for the matching area on the other image is initiated. This section describes the particular algorithms that have been substituted or added under the current work effort.

3.1 DATA MANAGEMENT

Previously the block processor was equipped with a data manager that would allow correlation to take place at random anywhere in the imagery. The cost of this flexibility was a reduction in speed.

Therefore, in the present effort the assumption was made that the imagery is to be traversed in an orderly manner from one end to the other, that is, from scan line 1 to scan line N. Data management, then, is greatly simplified, consisting of the maintenance of two buffer windows, one on each image of the stereo pair, that move across the image with the correlation process.

To illustrate this data management, reference is made to Figure 3-1. The buffer window on the independent image, hereafter to be called Image A, is wide enough to include the number of scan lines required for a predetermined patch width. The buffer window on the dependent image, to be called Image B, contains as many scan lines as is required for the patch size search area, and the estimated warp between Image B and Image A.

New scan lines are read into the buffers only when needed as the correlation patches progress across the image. Image matching occurs first for all patches in Image A whose centers lie on the same scan lines before the patches move on to subsequent scan lines and before new data is added to the buffers.

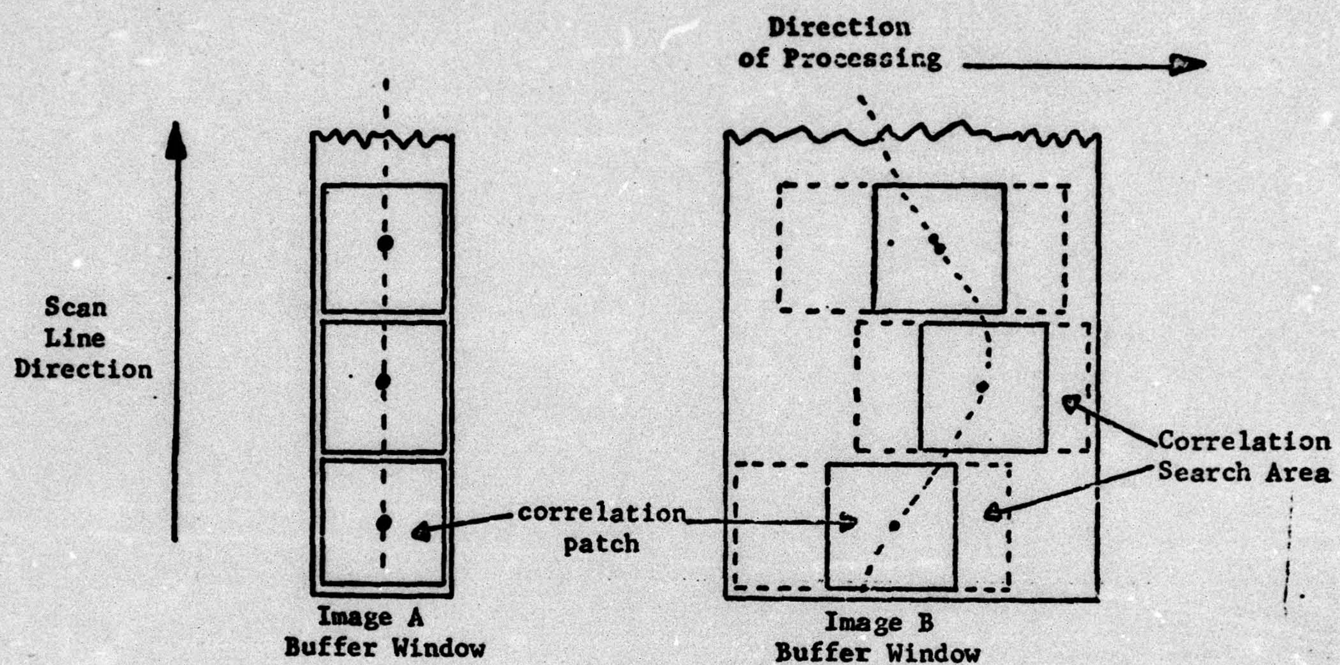
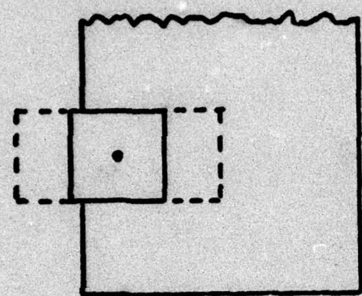


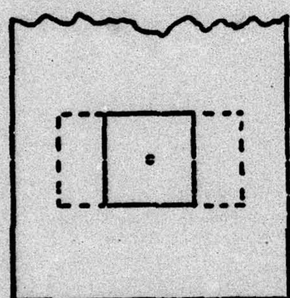
Figure 3-1 Data Management Scheme

Regarding the Image B buffer window, there are three distinct cases of buffer management that can occur for every match point determination. Figure 3-2 depicts these cases.

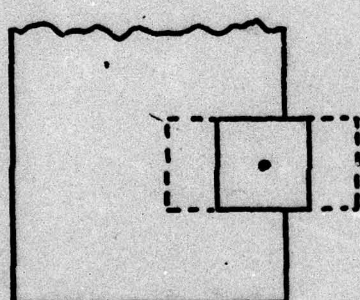
The optimum situation exists when the buffer window is wide enough such that case 1 does not occur.



Case 1 - Patch and search area behind current buffer window placement-- either enlarge buffer or back up the data



Case 2 - Patch and search area completely enclosed in buffer -- no buffer management necessary



Case 3 - Patch and search area ahead of current buffer window placement -- move window ahead by reading in more scan lines

Figure 3 - 2 Three Cases of Image B Buffer Management

3.2 CORRELATION ALGORITHM

In the determination of a match point, it is necessary to place the correlation patch center at each site of the Image B search area and accumulate over the patch area the necessary gray scale sums and cross products needed for the computation of the correlation coefficient. The net result is a value of the correlation coefficient for each site of the search area.

Previously in block matching systems, the computation of sums, cross products, and correlation coefficients has occurred in total for each distinct patch placement in the search area. In this scheme there are a great deal of redundant computations, and each Image B pixel is accessed repeatedly, once for each patch placement that it is contained in.

Under the current matching effort, the basic philosophy behind the correlation algorithm is to access each pixel only once for a given search and to accumulate its gray-scale value when it is available in all the sums and cross products for which it has influence. The actual correlation algorithm directs patch placement over a search area that extends in only one dimension around a predicted point on Image B. Thus, correlation values are generated on a line segment coincident with the epipolar line passing through the predicted point.

The mechanics of the algorithm are illustrated in Figure 3-3. As each pixel of the A image patch is accessed, its value is accumulated in the patch sum and sum of squares. Likewise, as each pixel of the B image search area is accessed, its value is accumulated in its respective column sum and column sum of squares. Also, cross products are generated for each patch placement along the Image B search segment. When the accumulation of sums and cross products is complete, the variance of the Image A patch is computed and the array of column sums and the array of column sums of squares are traversed to generate an Image B variance and a covariance for each site of the search segment. The array traversal involves the addition of the next

column sum and the subtraction of the last column sum from a running total to simulate the movement of the patch along the search segment.

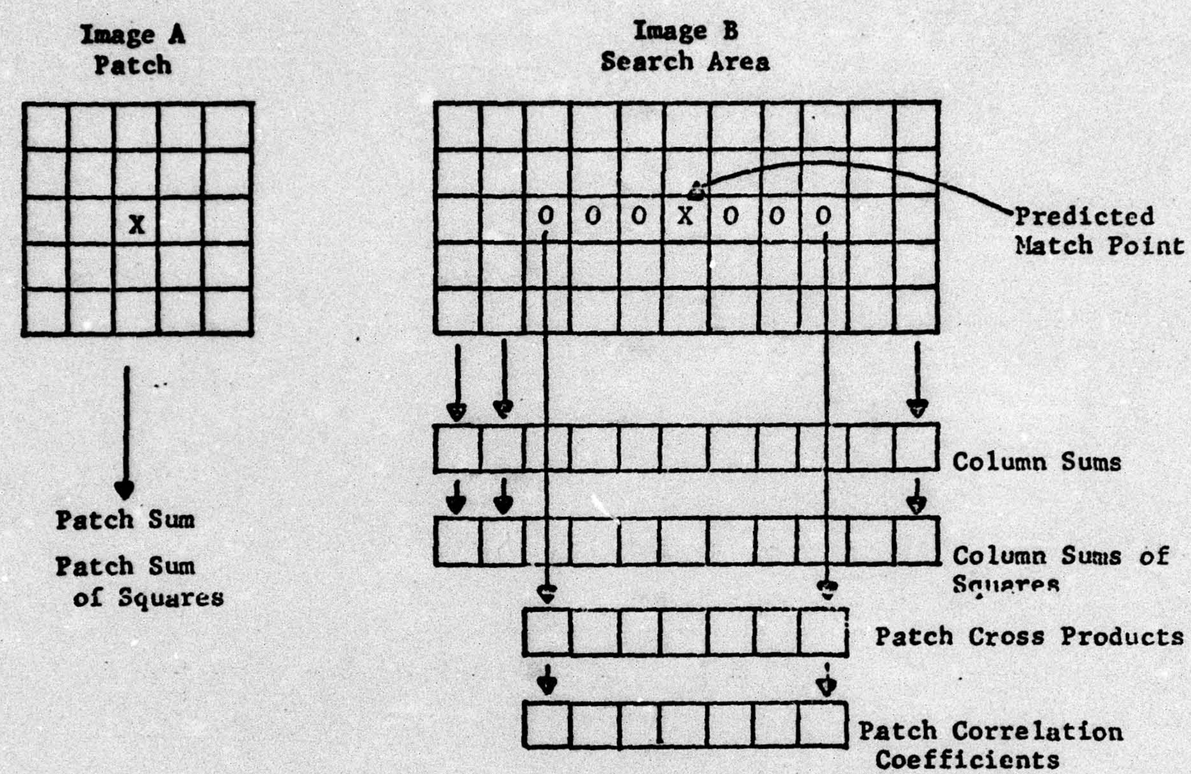


Figure 3-3 Correlation Algorithm Detail

The final result of the algorithm is an array of correlation coefficients of the form

$$r = \frac{\text{cov }(A,B)}{\sqrt{\text{var}(A)\ \text{var}(B)}} ,$$

one value for each placement of the patch along the search segment.

3.2.1 CORRELATION MAXIMUM DETERMINATION

It has been shown in previous studies that it is not sufficiently accurate for cartographic purposes to merely find the maximum value of the correlation coefficient along the search segment at a pixel center.

Rather it is necessary to interpolate the correlation maximum to a fraction of a pixel.

Referring to Figure 3-4, the correlation maximum at a pixel center is found and then by using one value on either side of this maximum, a parabolic curve is fit over the three values. The point along the search line segment at which the derivative of the parabolic curve is zero, is the point of maximum correlation.

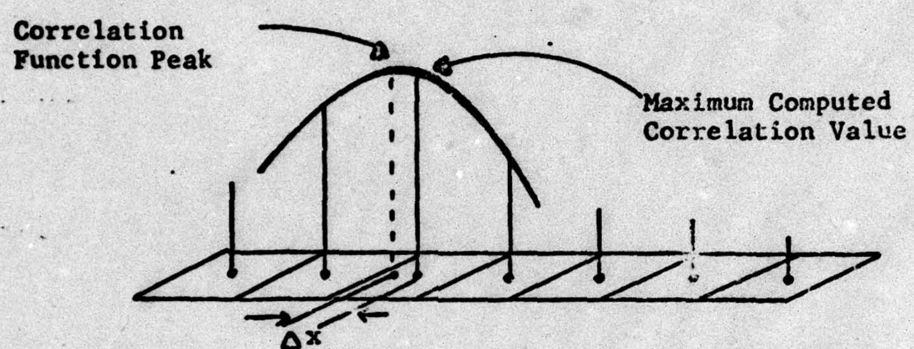


Figure 3-4 Correlation Maximum

A problem exists when the maximum correlation value at a pixel center occurs at either extremity of the search segment. In this case, a parabolic fit cannot be performed, and the algorithm is designed to flag this situation and return the pixel center as the point of maximum correlation. The underlying idea here is that this match point is suspect and a candidate for further processing.

3.2.2 MATCH POINT DETERMINATION

The result of one loop through the correlation algorithm is a pair of conjugate match points of the form (x,y,u,v) where x,y are the coordinates of the point on Image A and u,v are the coordinates on Image B. These points may be expressed by the algorithm in either digital scan coordinates or

photo coordinates.

Since the correlation algorithm performs the correlation search in only one direction, that is, along an epipolar line segement, what is really searched and found by gray-scale correlation is the u coordinate. The v coordinate of the match point is computed directly from epipolar geometry parameters; thus eliminating the need for a correlation search in the v direction.

3.3 PREDICTION SCHEME

Prediction in automatic matching systems involves the accurate acquisition of the next point to be used to center a search area based on previously matched points. In the previous block matching systems such prediction was made using a large number of match points (in the neighborhood of 20 to 30). Minimal use of stereo geometry was used in the prediction, and because of the large number of points used, the prediction was rather global in nature. This required the use of large correlation search areas to compensate for the local image deviations from the global prediction. However, it was found that large, two-dimensional search areas contributed to the instability of the prediction mechanism in hard-to-correlate areas.

Therefore, it was advisable in the current matching effort to design a prediction scheme that:

- uses as much stereo geometry as possible
- is more locally valid
- is accurate enough to reduce the search area to a minimum
- relies less heavily on the correlation coefficient

Such a predictor was implemented and is described in the following sections.

3.3.1 EPIPOLAR CONTROL

As was mentioned above, the correlation search for the v coordinate in the former matching system was replaced by the direct computation of the v coordinate from epipolar geometry. Referring to Figure 3-5, the large dots represent previous matched, conjugate points.

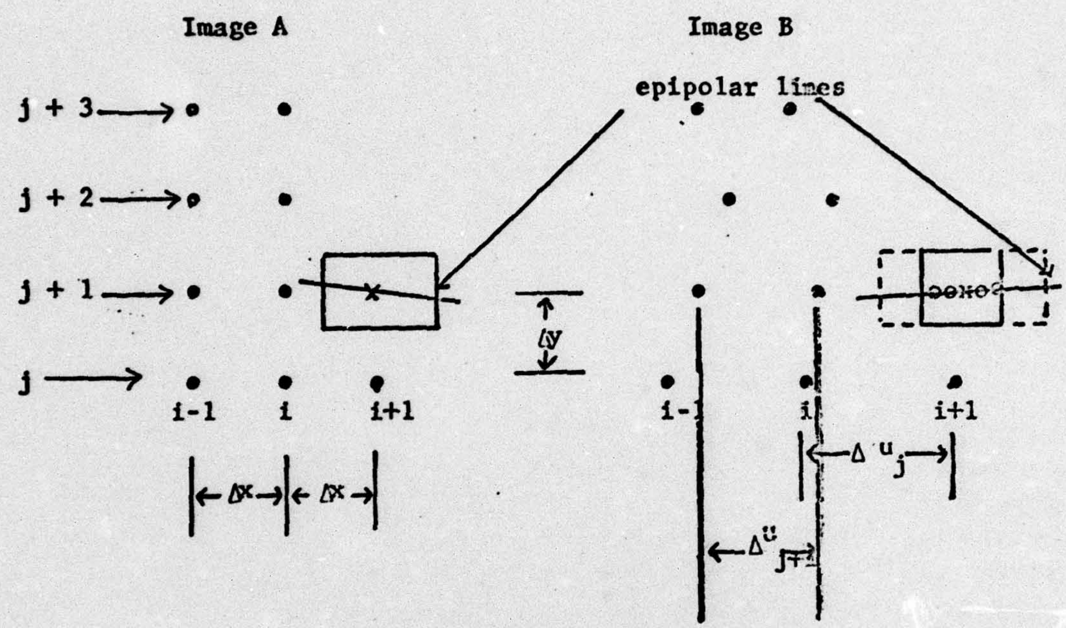


Figure 3-5 Prediction Mechanism

The x's within the patches indicate the points to be matched next. The sequence of matching over the Image A regular grid proceeds from point i,j to i,j+1 to i,j+2, etc. until one line of blocks is complete. Then matching continues with line i+1.

Using the photo coordinates of the center point of the patch i+1, j+1 on the A image and the relative orientation elements of Image B to Image A, the equations of corresponding epipolar lines are determined. Knowledge of where the epipolar line lies on the B Image essentially determines the v coordinate of the match point without need for a correlation search in the

v direction. What is necessary is an accurate prediction of the u coordinate along the epipolar line.

3.3.2 RATE OF CHANGE FUNCTIONS

The scheme used for predicting the u coordinate is based on $\Delta u/\Delta x$, the rate of change of the Image B u coordinate with respect to the Image A x coordinate. This function is kept and updated independently for each path of blocks, j, running along the images in the parallax direction. Δx is the predetermined, regular interval between match points on Image A and Δu's are computed for each path j as new match points are found. In Figure 3-5, for example,

$$\left[\frac{\Delta u}{\Delta x}\right]_j = \frac{u_{i+1} - u_i}{\Delta x} \qquad \text{and,}$$

$$\left[\frac{\Delta u}{\Delta x}\right]_{j+1} = \frac{u_i - u_{i-1}}{\Delta x}$$

To obtain a prediction for the u coordinate for match point pair (i+1, j+1), a combination of the neighboring values of $\Delta u/\Delta x$ may be used. For the present image matching effort, the following prediction formula was found most successful for the mountainous areas of the Phoenix imagery:

$$\hat{u}_{i+1,j+1} = u_{i,j+1} + \left(.6\left[\frac{\Delta u}{\Delta x}\right]_j + .4\left[\frac{\Delta u}{\Delta x}\right]_{j+1}\right)\Delta x$$

where $\hat{u}_{i+1,j+1}$ is a prediction to be refined by the correlation search. When the correlation algorithm has found the true match point $u_{i+1,j+1}$ along the epipolar line, then $[\Delta u/\Delta x]_{j+1}$ is updated using the new match point for that path and the prediction mechanism moves on to match location (i+1,j+2).

The advantage of such a prediction scheme is that it can be as local or as global as desired, depending upon how many and the placement of

neighboring rate of change functions that are used in a prediction. Moreover, the $\Delta u/\Delta x$ function is proportional to the actual terrain slope as it appears in terms of Image A. The following formulation and its derivations show this relationship:

$$\frac{\Delta u}{\Delta x} = 1 - \frac{\Delta h}{\Delta x}\,\frac{p_i p_{i+1}}{Bf}$$

where $\frac{\Delta h}{\Delta x}$ is the terrain slope with respect to the x coordinate, B is the baseline distance between exposure stations, f is the focal length of the cameras and p_i and p_{i+1} are parallax values over the interval in which the changes are computed. This equation holds only for truly vertical photo photographs and is set down here to point out that $\Delta u/\Delta x$ varies inversely with the terrain slope and is close to 1.0 in flat terrain. As depicted in Figure 3-6, $\Delta u/\Delta x$ takes on values different from 1.0 depending upon whether the terrain is ascending or descending in the process direction.

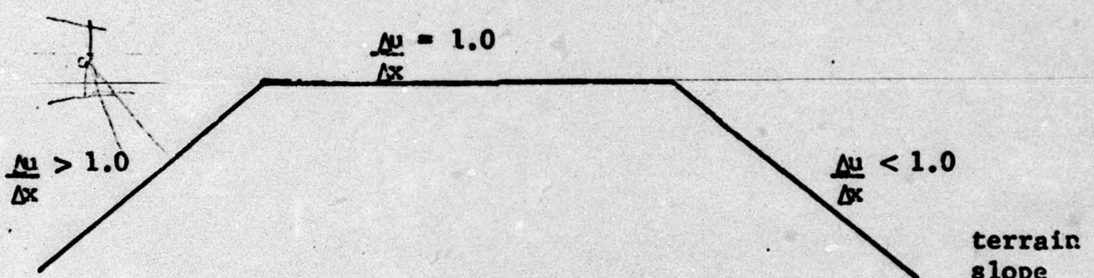


Figure 3-6 Effect of Terrain Slope on $\Delta u/\Delta x$ Function

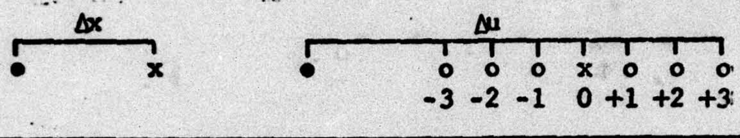
It has been found that for stereo base/height ratios in the neighborhood of 0.6 and for terrain slopes that do not exceed ± 45 degrees, the rate of change function is generally within the range:

$$0.5 \leq \frac{\Delta u}{\Delta x} \leq 1.5$$

In terms of automatic matching, the stability of a prediction mechanism using the $\Delta u/\Delta x$ function is very much dependent on both the choice of Δx and the size of the B Image search segment in scan lines.

The rationale behind the optimum choice of these parameters is to obtain a prediction within the allowable limits of the $\Delta u/\Delta x$ function so that correlation is performed in but a minimum area. In this way, less emphasis is placed on the correlation coefficient finding a reliable match point over an extended area. Table 3-1 hypothesizes a 7-line search segment centered at a predicted point and summarizes the behavior of the $\Delta u/\Delta x$ function for given values of Δx and for a correlation maximum occurring at each site of the search segment.

Table 3-1 THE EFFECT OF SEARCH SEGMENT SIZE ON THE $\Delta u/\Delta x$ PREDICTING FUNCTION



Δx (Scan Lines)	Δu (In Lines from Predicted Point)						
	-3	-2	-1	0	+1	+2	+3
	$\Delta u/\Delta x$						
1	-2.0	-1.0	0.0	1.0	2.0	3.0	4.0
2	-.5	0.0	.5	1.0	1.5	2.0	2.5
4	.25	.5	.75	1.0	1.25	1.5	1.75
8	.625	.75	.875	1.0	1.125	1.25	1.375
12	.75	.833	.916	1.0	1.083	1.166	1.25
16	.812	.875	.937	1.0	1.062	1.125	1.187

The table is set up for the case where the center of the search segment is at $\Delta u=\Delta x$, the case of flat terrain starting an inflection upward or downward.

The dashed area of the table indicates the search segment lengths that

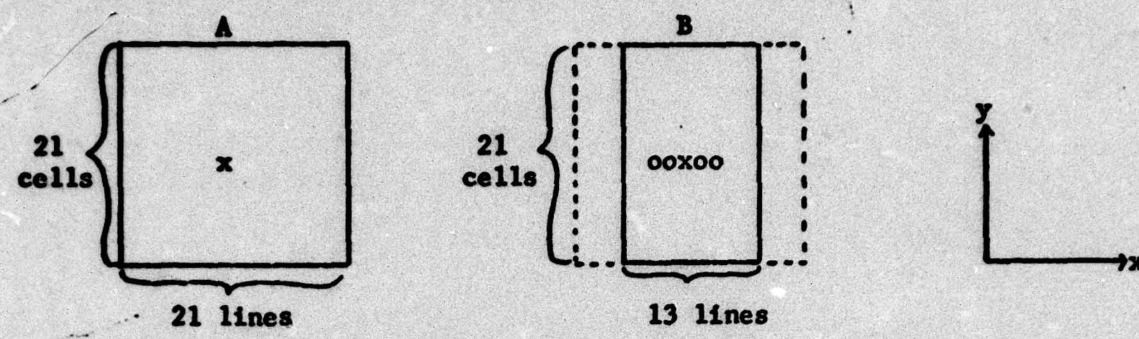
are critical for maximum stability of prediction for various values of Δx. That is, for Δx values of 2, 4 and 8, the optimum search segment lengths are 3, 5 and 7 respectively. What this means, for example, is that if a 7-line search segment were used with a Δx of 2 lines and further, if the area being searched is lacking in feature or grossly dissimilar on both images, then the probability is great that the correlation algorithm will find a correlation maximum toward the ends of the search segment. Thus the $\Delta u/\Delta x$ function value becomes too low or too high, resulting in a biased next prediction. It has been observed in these cases that succeeding correlation maximums along a path are found alternately at one end of the segment and then the other, causing the $\Delta u/\Delta x$ function to oscillate rapidly until good feature lock-on can be achieved or until the prediction mechanism totally degenerates.

For larger values of Δx, say 12 or 16 lines, a 7-line search segment is unresponsive to rapid terrain changes. In these cases, the search segment length must be increased. For the current matching effort, a 7-line search segment with a Δx value of 8 lines has been found to produce the best results. Of course, this is very much dependent upon the scale of the imagery and the type of terrain being matched.

3.3.3 CORRELATION PATCH SHAPING

The $\Delta u/\Delta x$ function is not only a valid metric for prediction purposes but also for measuring the amount of local Image B compression or expansion relative to the same area on image A. In previous block matching systems, a correlation search was performed using patches of equal size on the A and B Images. It was found, however, that this procedure is valid only in flat terrain, that is, where $\Delta h/\Delta x$ is close to zero and $\Delta u/\Delta x$ is close to 1.0. For all other cases, the B Image patch must be compressed or expanded primarily in the major parallax direction. Referring to Figure 3-7 as an example, if the size of the Image A patch is chosen as 21 x 21 cells and the current $\Delta u/\Delta x$ function is .6, then the corresponding patch on the B Image is

21 cells by 13 lines. The Image B patch and search



$$\frac{\Delta u}{\Delta x} = .6$$

Figure 3-7 Patch Shaping

area height remains at 21 cells because the image y parallax is negligible in terms of whole pixel intervals.

As a further sophistication of patch shaping, the B Image patch sides (the 21-cell dimension of the figure) may be slanted to account for Image B warp due to terrain slope in the y direction.

The correlation coefficient for these patches must be computed using 21 x 21 pixel samples. Therefore, the Image B patch area must be resampled to derive 21 x 21 gray-scale values from the 21 x 13 pixels that are contained in the patch area. In the current implementation of the block matching system, the entire search area is shaped according to the $\Delta u/\Delta x$ function and a synthetic search area is generated which contains the required number of samples for the correlation algorithm.

The need for patch shaping in other than flat terrain is corroborated in Table 3-2. The table hypothesizes that the correlation patch size is the same on both the A and B Images, and computes the percentage of unwanted gray-scale samples that effect the correlation coefficient over terrain sloping upward in the process direction. B Image patch shaping eliminates these unwanted samples.

Table 3-2 THE AMOUNT OF STATISTICAL INFLUENCE OF AN UNSHAPED, OVERSIZE IMAGE B PATCH

$\frac{\Delta u}{\Delta x}$	Image A & B Square Patch Size a	Image B Shaped Patch Size b	# Scan Lines Too Many a-b	# Pixels Too Many a(a-b)	% of Unwanted Patch Area 100(a-b)/a
.9	11	10	1	11	9.1
	15	14	1	15	6.7
	21	19	2	42	9.5
	25	23	2	50	8.0
	31	28	3	93	9.7
.8	11	9	2	22	18.2
	15	12	3	45	20.0
	21	17	4	84	19.0
	25	20	5	125	20.0
	31	25	6	186	19.4
.7	11	8	3	33	27.3
	15	11	4	60	26.7
	21	15	6	126	28.6
	25	18	7	175	28.0
	31	22	9	279	29.0
.6	11	7	4	44	36.4
	15	9	6	90	40.0
	21	13	8	168	38.1
	25	15	10	250	40.0
	31	19	12	372	38.7

A secondary conclusion that can be drawn from the table is that the need for patch shaping is independent of patch size. However, this is valid only when the $\Delta u/\Delta x$ function remains constant over the patch area. Also, the larger the patch, the more non-linear the sides of the patch in the y direction become.

3.4 DISSIMILAR IMAGE AREAS

As was described above, correlation subregions move across the images in the major parallax direction in paths. Each path is basically independent of the others, being controlled by its own $\Delta u/\Delta x$ function. But because the paths are independent, it is not uncommon in featureless areas or areas that are dissimilar in gray-scale on the two images for blocks in a given path to wander, that is, fall excessively behind or move ahead of blocks in adjacent paths. The wandering usually occurs when the lack of correlation lock-on causes the $\Delta u/\Delta x$ function for that path to become unstable.

Therefore, a mechanism has been provided in the current block matching system to detect wandering blocks and to correct their position, based on blocks in adjacent paths. This harnessing technique is shown in Figure 3-8.

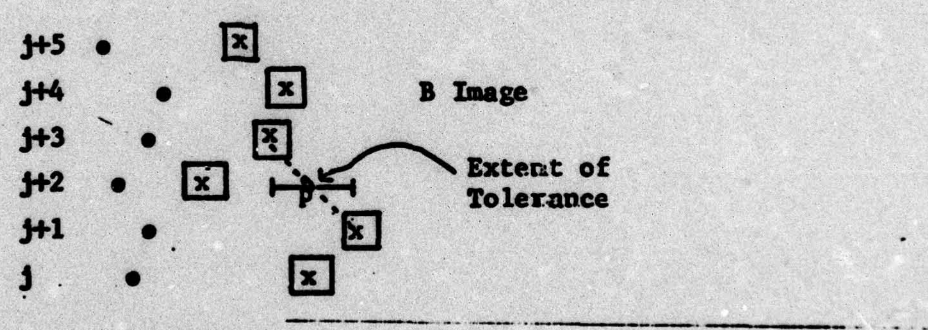


Figure 3-8 Wandering Block

When the processing of a complete line of blocks (blocks which have the same digital x coordinate im Image A) is complete, a check is made to see that all blocks lie within a predetermined tolerance distance from the

average position of the blocks in adjacent paths. If not, the position of the wandering block and the $\Delta u/\Delta x$ function for that path are corrected accordingly. Referring to the figure, the block on path j+2 has been detected as wandering. Its position is corrected to point P, the average position of paths j+1 and j+3.

A special case exists for the end paths, paths j and j+5 of the figure, where complete harnessing is not possible. A problem also exists when blocks in more than one path begin to wander. The probability of this occurance on good imagery is rather low, but when it does occur, the described mechanism can correct the wandering blocks iteratively over a longer stretch of imagery. When all paths become lost, there is not much that can be done.

4.0 PROCESSING RESULTS

A digital stereo pair of images was received from USAETL with all the appropriate interior orientation transformations and exterior orientation parameters. The digital image data represents a four square inch scene from the 1:48000 Phoenix-South Mountain model. Digital encoding was performed at ETL with a 35 micrometer spot size and a 24 micrometer sampling interval. A pixel, therefore, represents a nominal 4 feet on the ground.

Supplied with the imagery was also a file of 25,250 match points generated by an ETL block process. These match points covered an image area of approximately .25 inches by .5 inches at original image scale and were used to initialize both the CDC strip process and block process.

The modified strip process and block process as described in the sections above were applied to the same image area and files of match points were generated. For the strip processing, the strip centers were located 10 pixels apart and the strip width was chosen as 20 pixels. The effective recursive correlation area along the strips was chosen as 6 scan lines. Even though the strip process provides line-by-line tracking of an image, match points were output every 8 scan lines, thus providing a match point lattice whose interval is 10 pixels in the y direction by 8 lines in the x direction.

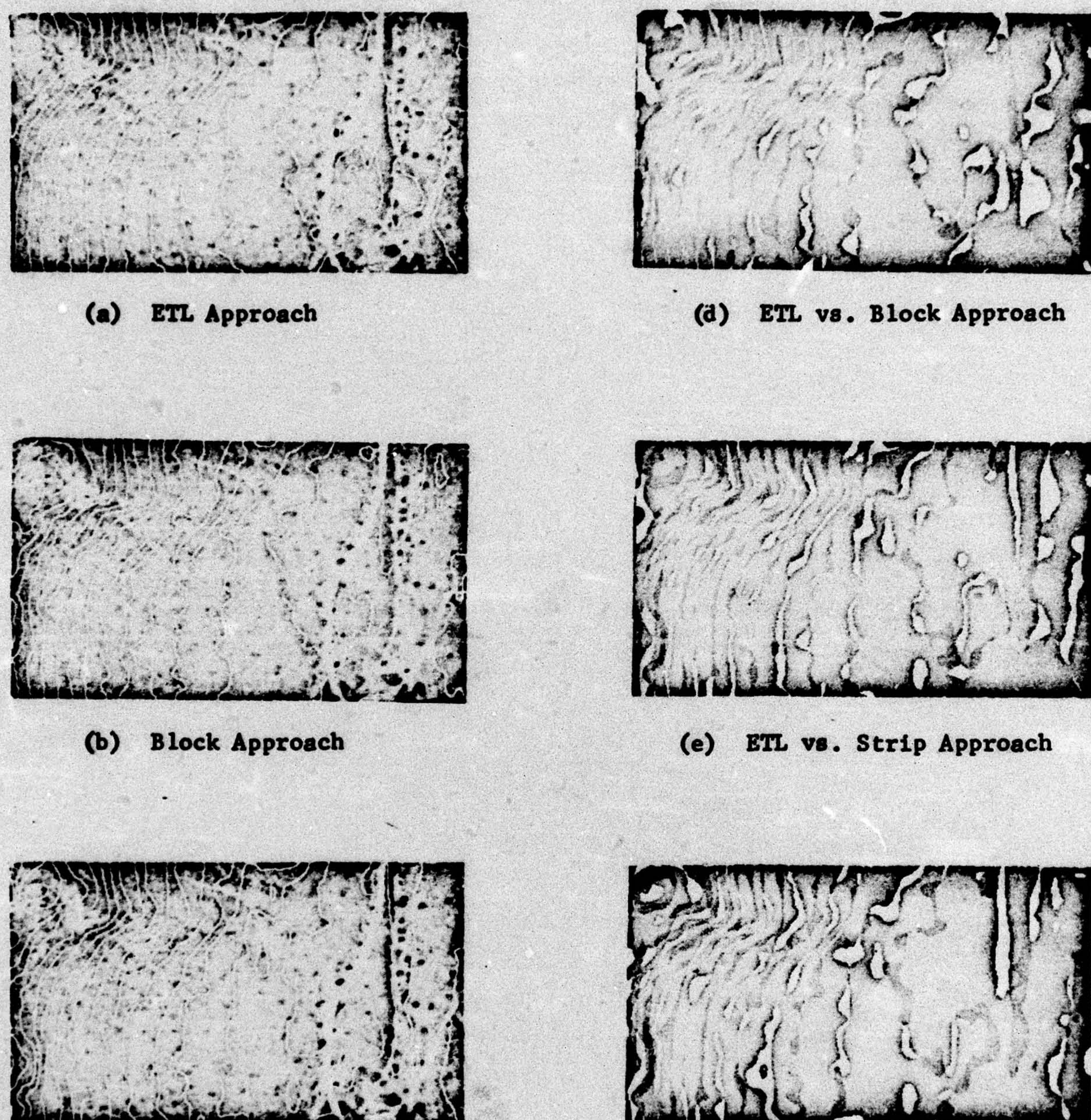
In both processes, Frame 98 of the stereo pair was chosen as Image A, the independent image, and Frame 99 as Image B or the dependent image. For the block process, a correlation patch size of 21 x 21 pixels on Image A was chosen. The distance between blocks or block paths on Image A was 10 pixels and Δx or the block jump-interval was 8 lines. A 7-line search segment was used on Image B, including three scan lines on either side of a predicted point.

As a result, three match point files were available for analysis; the ETL file, the block file, and the strip file. These files were processed using photogrammetric intersection to obtain for each point an orthometric terrain

elevation in feet above the earth. These elevations were given X,Y coordinates corresponding to the digital raster of Image A. Therefore, the resultant terrain data is not truly orthographic, but rather as unrectified as Image A.

These files of terrain data were fit with local, smooth bicubic polynomials to produce the contour lines shown in Figure 4-1(a,b,c). The contour interval is 20 feet and the background is the Image A section. This section of image has been enlarged 8 times, the original scale area being approximately .25 inches by .5 inches. To point out the differences between approaches, contour difference images were generated and appear in Figure 4-1(d,e,f). These difference images were produced by subtracting corresponding contour region images, where the 20 feet contour regions are alternately colored black and white. The neutral gray color indicates similarity between contour regions or zero in the subtraction. The white and black contour differences change polarity on every contour region. Therefore, visual reference must be made to Figure 4-1(a,b,c) to determine which difference in Figure 4-1(d,e,f) came from which image. It must be kept in mind that because the terrain elevations have been quantized into discrete 20 feet intervals to produce the difference images, the actual magnitudes of the differences observed can range between 0 and 20 feet. As a quantitative measure, the RMS magnitude of the actual orthometric elevation differences is in the neighborhood of 8 feet for all three cases.

The processing of the Phoenix model using the strip approach and block approach was extended beyond the ETL match point data to include about 12,000 match points across the entire length of the digital sample. The results of this processing in contour line form along with the contour differences appear in Figure 4-2. These images are enlarged 4 times. The actual image area is approximately .5 by 2 inches at the original scale of the photography.



(a) ETL Approach

(d) ETL vs. Block Approach

(b) Block Approach

(e) ETL vs. Strip Approach

(c) Strip Approach

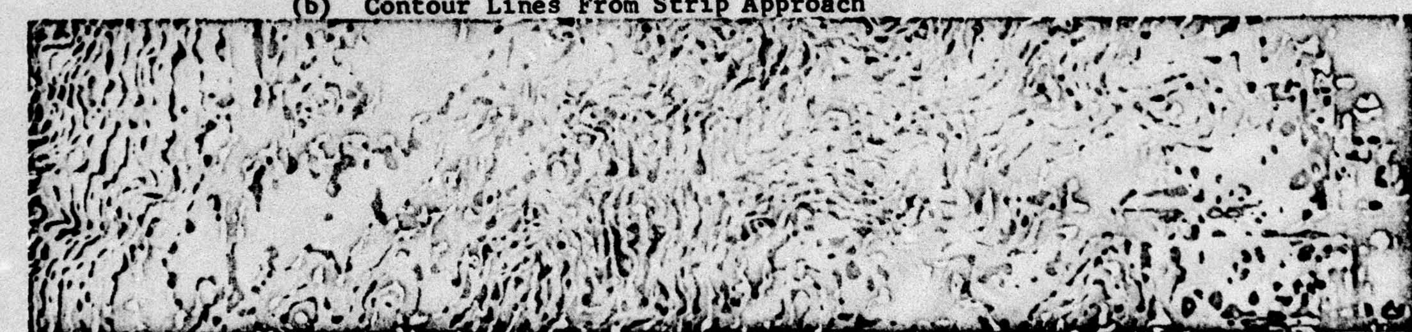
(f) Block vs. Strip Approach

Figure 4-1. Comparison of Matching Approaches in Terms of Contoured Terrain Data

a,b,c - Contour Images, 20 feet interval
d,e,f - Contour Difference Images

(a) Contour Lines From Block Approach

(b) Contour Lines From Strip Approach



(c) Contour Differences - Block Approach vs. Strip Approach

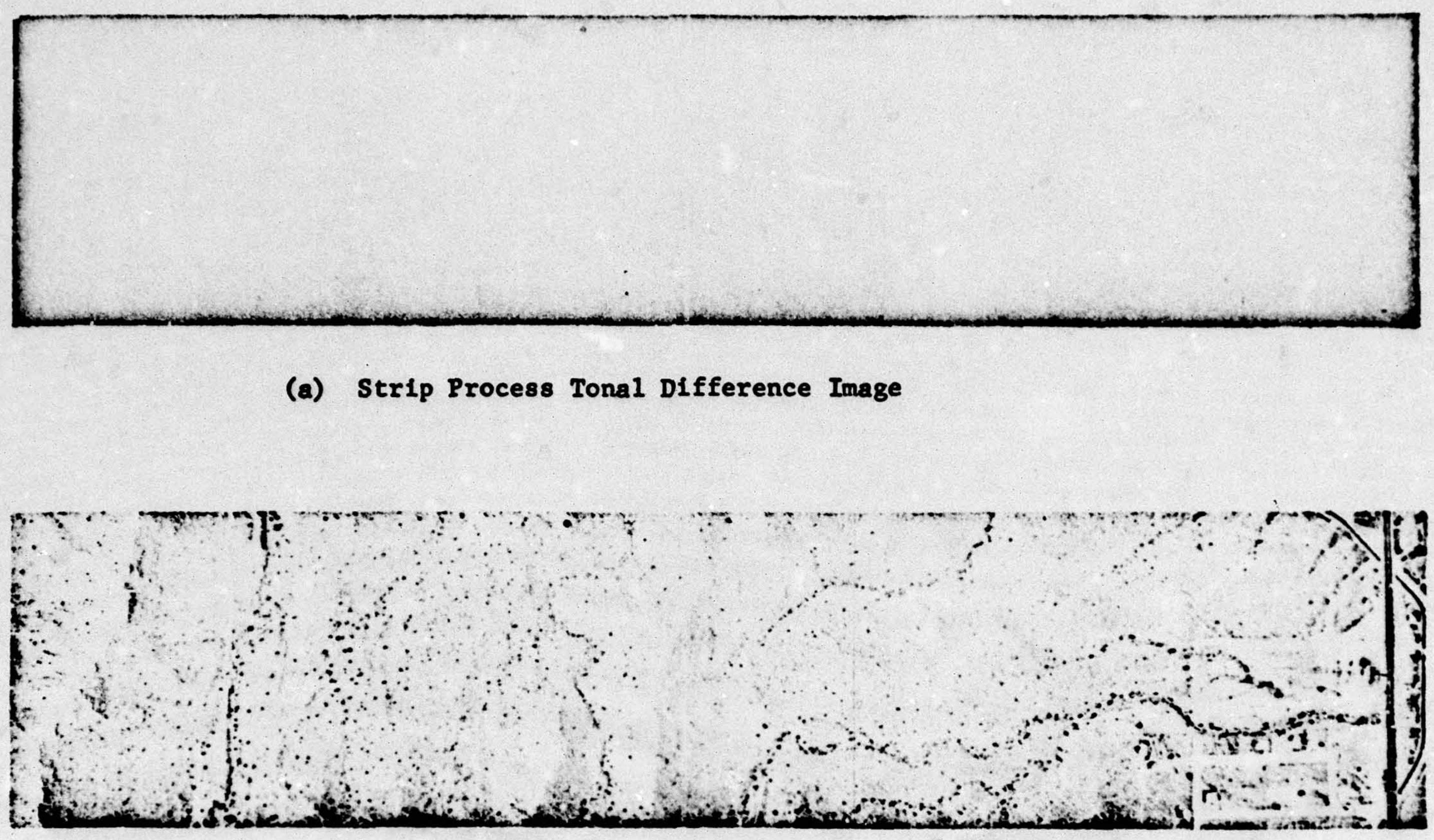
Figure 4-2. Comparison of Matching Approaches Over A Larger Area

A by-product of the strip approach is the warping of the B Image to register with the A Image and also the generation of a tonal difference image for change detection purposes. This difference image and the corresponding unrectified section of Image B as reference are shown in Figure 4-3.

The tonal difference image is a qualitative measure of the goodness of match for the strip approach. As can be seen in the image, the only real gray scale differences after registration are the reseau marks and the dissimilar appearance of the tall buildings in the right of the scene. Referring back to Figure 4-2, it can also be seen that some of the buildings were contoured as part of the terrain by the strip approach. But despite this goodness of registration, the actual RMS differences in elevation between the strip approach and the block approach for the 12,000 match points was again about 8 feet.

As a further demonstration of the performance of the two approaches, the raw terrain data, without fitting or smoothing, that was produced by intersection from the match points was plotted in a three-dimensional mode on a Calcomp plotter. These plots appear in Figures 4-4 and 4-5. Each plotted line in these figures represents one profile in the y direction. As was mentioned before, the interval between profiles is 8 scan lines. The vertical dimension in these plots has been greatly exaggerated to emphasize small-scale differences between the approaches. It can be seen that the strip process produces a more noisy data set.

Regarding processing speed, the general purpose implementation of the block approach as described above produces 14 match points per central processor second. The strip approach produces 27 match points per second. This figure for the strip approach is based on a match point every 8 scan lines. But because the strip process performs correlation on a scan line-by-scan line basis, the capability exists for generating a match point for each strip on every scan line at no extra time. Therefore, the process can produce up to 216 match points per second. Both the block process and strip process are implemented in FORTRAN running on the CDC 6600 computer system.



(a) Strip Process Tonal Difference Image

(b) Original Section of Frame 99

Figure 4-3. Strip Process Registration Evaluation

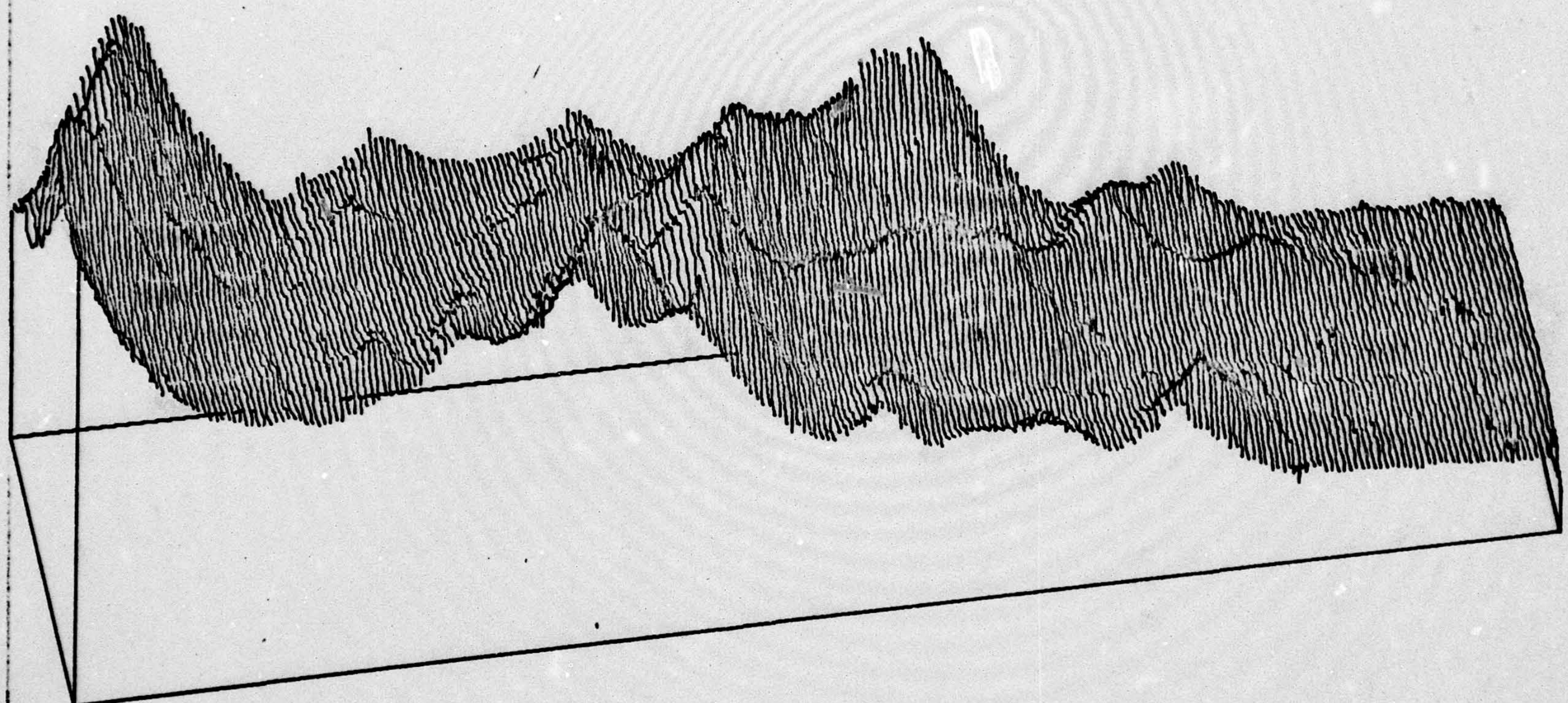


Figure 4-4. 3-D Plot of Block Process Terrain Data

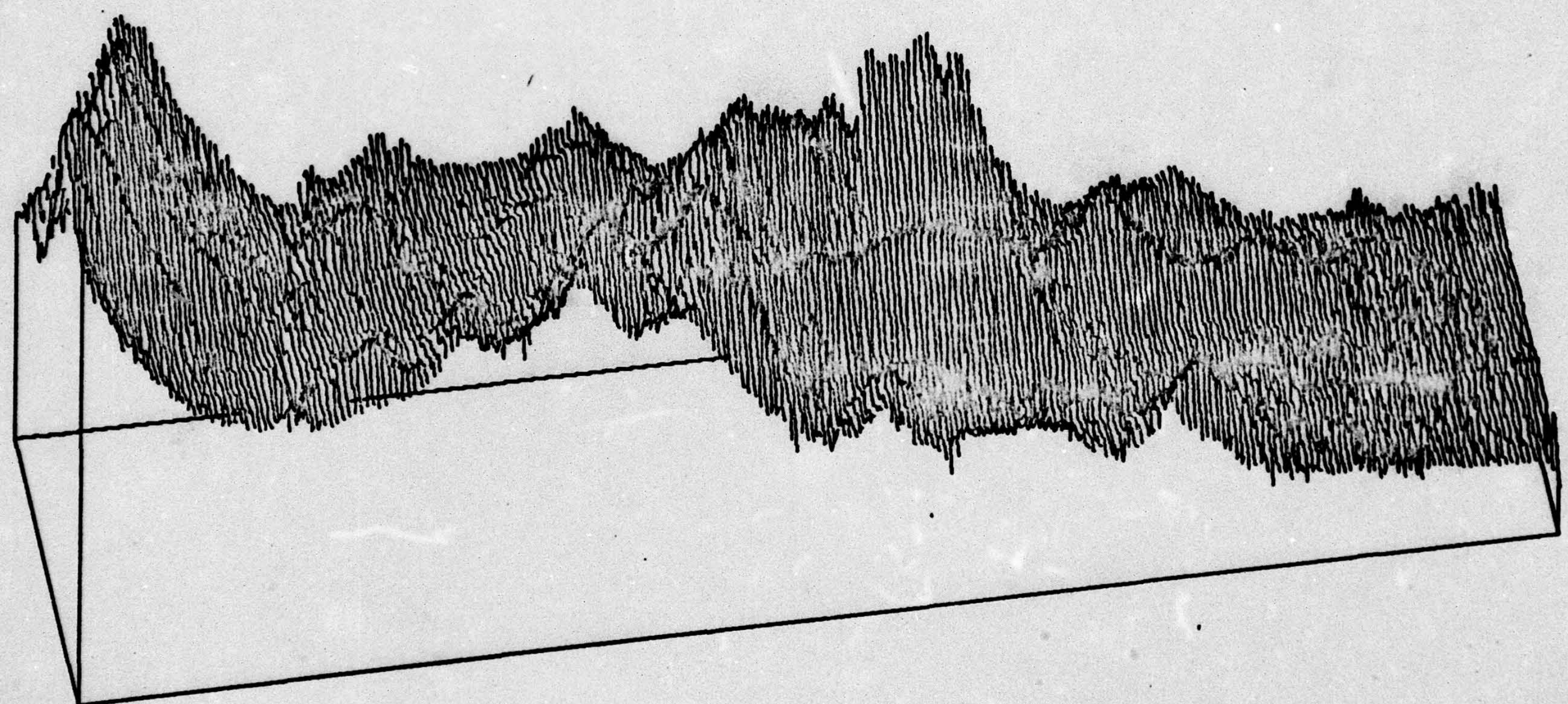


Figure 4-5. 3-D Plot of Strip Process Terrain Data

5.0 CONCLUSIONS

It can be seen from the contour images presented above that both the strip approach and the block approach in their present implementations are following the general terrain trends of the imagery. It is conjectured that if the terrain data from the two approaches were evaluated against known ground or model control points using standard photogrammetric techniques, the RMS deviations at the control points would be very small. This is due to the fact that control points are generally associated with well-defined features, which features can be matched very well by an automatic process. It is the featureless, between-control-point areas that pose problems both for automatic matching and terrain data evaluation.

The strip approach is a very fast production-oriented process. But the digital terrain data it generates is rather noisy. This seems to be an attribute of the line-by-line, error correcting nature of the process. By placing constraints on the process smoother terrain data results, but the process becomes less responsive to terrain fluctuations. That is, the process tends to overshoot mountain peaks and to dig into valleys.

The block approach, on the other hand, generates less noisy terrain data due to its deterministic predict-ahead mechanism. The values of the correlation coefficient are generally higher in the block approach than in the strip approach and the match points generated in feature-rich image areas seem to be more accurate in the block approach. However, in featureless and dissimilar image areas the block process has less system inertia to carry it through the difficult regions than the strip process. In addition, the block process is slower.

With all these tradeoffs in mind, the block process is being considered further for implementation in the digital cartographic benchmark.

REFERENCE

1. Bonrud, L. O. et al., "Analysis and Development of Digital Mapping System Software," Final Report to U. S. Army Engineer Topographic Laboratories, ETL-CR-74-5, May 1974.